SHELTER MODELS FOR CONSEQUENCE ANALYSIS AND RISK ASSESSMENT OF CO₂ PIPELINES

J.M. Race\textsuperscript{a}, K. Adefila\textsuperscript{a}, B. Wetenhall\textsuperscript{b}, H. Aghajani\textsuperscript{b}, B. Aktas\textsuperscript{b}

\textsuperscript{a} Department of Naval Architecture, Ocean and Marine Engineering, University of Strathclyde
\textsuperscript{b} School of Marine Science and Technology, Newcastle University
• Requirement for a shelter model
• Description of models developed
  – Analytical model
  – Computational Fluid Dynamics (CFD) model
• Model validation – single room
• Sensitivity study
• Effect of partitions and half height clouds
• Conclusions and recommendations
What is the CCS transportation challenge?

To transport anthropogenic CO$_2$ of varying composition from multiple capture sites (power plant and industrial) to multiple storage sites in a **safe**, reliable and efficient manner in compliance with appropriate design standards and regulatory requirements.
CO₂ is not explosive or inflammable like natural gas and is odourless.
CO₂ is denser than air and might accumulate in depressions or valleys.
CO₂ is toxic and above concentrations of ~10% can have long term effects or cause fatality.

Therefore
- Need to be able to calculate CO₂ concentrations around a failure in order to define separation distances from pipelines using a Quantitative Risk Assessment approach.
- Requires a pragmatic infiltration model to predict effect CO₂ exposure on humans in buildings.
Consequences of CO$_2$ pipeline failure

- CO$_2$ concentration profile outside the building
- CO$_2$ concentration profile within the building

(Time since release event vs. CO$_2$ concentration graph)

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Analytical model description

• Based on the principles of natural building ventilation (Etheridge and Sandberg, 1996).
• Model described in outline in Lyons et al 2015 and in detail in future publications
• Considers wind driven and buoyancy driven air flow.

Assumptions:
- Initial concentration of CO$_2$ in building is same as atmosphere.
- Building is engulfed in a cloud of CO$_2$ following a release

Air flow – wind driven

- Wind blowing outside.
- Pressure difference between internal and external environments.
- Air flows from high to low pressure - in at front face, out at rear.
- Air flow straight through building.
Air Flow – buoyancy driven

In the absence of a release:

- Increased internal air temperature reduces internal air density.
- Steeper pressure gradient outside the building than inside (as density is greater outside).
- Creates pressure difference across openings at top and bottom of building.
- Warm, less dense air leaves and is replaced by colder more dense air at base, with upward drift of warmer air inside.
CFD model

- Based on conservation equations for mass, momentum, energy and chemical species
- \( k - \epsilon \) turbulence model was corrected to incorporate the effect of buoyancy driven flows with low Reynolds number
- Four different models tested - Lag Elliptic Blending (EB) \( k - \epsilon \) model gave best results relative to the experimental data
- Meshed using polyhedral mesh within solution domain with a prism layer mesher used to improve the CFD simulation in near-wall regions
Model input data

Cloud conditions
- CO₂ concentration profile
- Temperature profile

Atmospheric conditions
- Wind speed
- Wind incident direction
- Internal temperature
- Internal CO₂ concentration

Building geometry
- Area of openings
- Spacing of openings
- Volume of building
Model comparison – single room totally engulfed

- Room dimensions: 6x6x3m
- Wind speed = 5m/s
- Window area = 0.02905m²
- Initial internal temperature = 293K

- CFD Analysis
- Analytical model

CO₂ concentration within the building (%) vs. Time from release event.
Toxic dose

- A generalised equation for toxic dose of exposure to some contaminant is given by:

\[ D = \int c(t)^n dt \]

Where
- \( c(t) \) is the concentration of the contaminant a person is exposed to in parts per million (ppm),
- \( t \) is the time of the exposure in minutes
- \( n \) is the toxic index = 8 for \( \text{CO}_2 \)

- **Dangerous Toxic Loads**
  - The Specified Level of Toxicity (SLOT). The SLOT dose for \( \text{CO}_2 \) is \( 1.5 \times 10^{40} \) ppm\(^8\).min.
  - The Significant Likelihood of Death (SLOD). The SLOD dose for \( \text{CO}_2 \) is \( 1.5 \times 10^{41} \) ppm\(^8\).min.
Model comparison – single room totally engulfed

Room dimensions: 6x6x3m
Wind speed = 5m/s
Window area = 0.02905m²
Initial internal temperature = 293K

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Sensitivity study – wind speed dependence

Room dimensions: 6x6x3m
Wind speed = variable
Window area = 0.02905m²
Initial internal temperature = 293K

Toxic Dose (ppm²·min⁻¹)

Time from release event

- 20m/s
- 10m/s
- 5m/s

SLOD
Partitions and half height clouds

Room dimensions: 6x6x6m
Wind speed = 5m/s
Window area = 0.02905m² for each window
Initial internal temperature = 293K

CO₂ concentration within the building (%)

Time from release event

- CFD analysis - top floor
- Analytical model - top floor
- CFD analysis - bottom floor
- Analytical model - bottom floor
Conclusions

- Two shelter models have been developed as part of this work; an analytical and a CFD model.
- The models compare favourably with experimental test data.
- It has been demonstrated that the ability of buildings along a pipeline route to provide shelter can be determined using these models.
- The wind speed has been shown to have the greatest impact on concentration profiles within the building.
Conclusions

- Calculations have been conducted for worst case direction.
- SLOD times would be different (and less severe) for different directions throughout the cloud.
- In conducting a full QRA a failure frequency analysis would be incorporated with these results to calculate the risk at any particular location.
- However, it has been shown that dose received by an individual in a building would not reach the levels of toxicity experienced in shelter were not considered.
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